MS95: Lagrangian Traffic Flow Control and Autonomous Vehicles

2017 SIAM Annual Meeting

Minisymposium Synopsis

- Current traffic flow control: variable speed limit signs, ramp metering, traffic lights.
- Current control objective: maximize throughput of road (network).
- New and upcoming disruptive technologies: mobile GPS sensors, autonomous vehicles.
- This research: How to use them for future traffic flow control.

Ongoing Revolution in Vehicular Transportation

Traffic assignment

1981–2014: in-vehicle navigation, no effect on traffic patterns
2014: Waze creates traffic jams in residential areas
future: feedback from route choices to traffic patterns $\longrightarrow$ Nash equilibria

Traffic flow state estimation

1933–2008: fixed sensors counting vehicle flow and occupancy *(Eulerian)*
since 2008: low density in-vehicle GPS [Mobile Millennium Project] *(Lagrangian)*

Traffic flow control

1963–today: ramp metering, variable speed limits, traffic lights *(Eulerian)*
near future: connected vehicles, control via autonomous vehicles *(Lagrangian)*
far future: vehicle-to-infrastructure communication, platooning AVs

Traffic optimization

1940–today: maximize flow rate (large-scale equilibrium behavior)
future: flow dynamics (vehicle scale); minimize fuel consumption, pollution, accident risk, etc.; possible due to surge in new data

Traffic Flow Control via Autonomous Vehicles (AVs)

- Traditional Eulerian highway traffic controls (ramp metering, variable speed limits) cannot affect traffic on the scale of waves. AVs can!
- Inexpensive: AVs will be on our roads anyways.
- Key question: Can AVs have a noticeable benefit on the overall traffic flow even at very low penetration rates?

Impact

- Dawn of a new era in vehicular transportation.
- Eulerian $\longrightarrow$ Lagrangian; local $\longrightarrow$ non-local.
- New types of data; new rules (connection and autonomy).
- The reality of traffic flow is changing. New and better mathematical traffic models are needed to understand the challenges and opportunities before we expose human drivers to the new reality.
- Cross-disciplinary effort: modeling, civil engineering, control theory, robotics, data science, computing, etc.

Lagrangian Traffic Flow Control and Autonomous Vehicles

Benjamin Seibold, Temple University	Traffic Flow Control and Fuel Consumption Reduction via Moving Bottlenecks
Raphael Stern, University of Illinois Urbana-Champaign	Controlling Stop and Go Traffic with a Single Autonomous Vehicle: Experimental Results
Rahul K. Bhadani, University of Arizona	Analysis and Design of Velocity Controllers for Dissipation of Stop-and-Go Traffic Waves
Thibault Liard, Rutgers University	On Well-Posedness and Control of a Moving Bottleneck Model

Traffic Flow Control and Fuel Consumption Reduction via Moving Bottlenecks

Rabie Ramadan and Benjamin Seibold* (Temple University)

2017 SIAM Annual Meeting

July 14th, 2017

Research Support

NSF CNS–1446690

CPS: Synergy: Control of vehicular traffic flow via low density autonomous vehicles

TEMPLE UNIVERSITY

Larger Project [with D. Work (UIUC), B. Piccoli (Rutgers), J. Sprinkle (U of A), NSF CNS–1446690, *CPS: Synergy: Control of veh. traffic flow via low density autonomous vehicles*].

- Real traffic flow exhibits undesirable features due to collective human behavior (stop-and-go waves, inefficient driving, etc.).
- Once all vehicles are autonomous, we can design AV controls that produce much better flow (string stability, platooning, etc.).
- Before that, we will have a mixed flow (humans and AVs). More complicated. Full understanding requires good human-driving models.
- Project: What can be done if very few vehicles ($<5\%$) are autonomous?

This Particular Project: Flow Control via Moving Bottlenecks

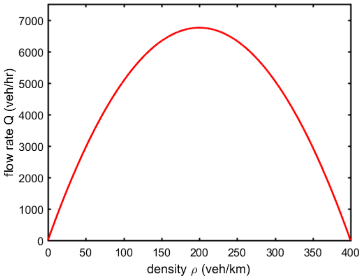
- A single AV is controlled to drive slower than the other vehicles.
- The AV will serve as a moving bottleneck on the highway.
- This may modify the traffic state on the road, by creating new states.
- In certain situations, this control can be beneficial (here: save fuel).
- Control via AV does not remove congestion, but it reduces its adverse effects.

UNIVERSITY

Macroscopic Flow Description

- Position along road: x; time: t.
- Vehicle density $\rho(x,t)$: #vehicles per unit length of road (at a fixed time)
- Flow rate $Q(x,t)$: #vehicles per unit time (passing a fixed position)
- Both ρ and Q possibly aggregated over multiple lanes.

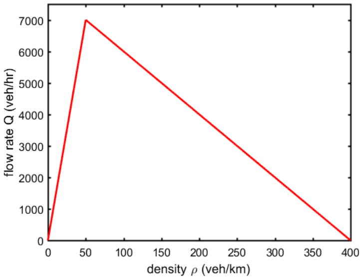
Greenshields Fundamental Diagram



Conservation of Vehicles Principle

$$\rho_t + Q_x = 0\ , \quad \text{where } Q = \rho u\ .$$

Newell-Daganzo Fund. Diagram



Lighthill-Whitham-Richards (LWR) Model

Assume $u = U(\rho)$. Thus: $Q = Q(\rho)$.

Hyperbolic conservation law:

(a) information propagation ($s = Q'(\rho)$)

(b) shocks ($s = \frac{Q(\rho_-)-Q(\rho_+)}{\rho_- - \rho_+}$)

Fixed Bottleneck

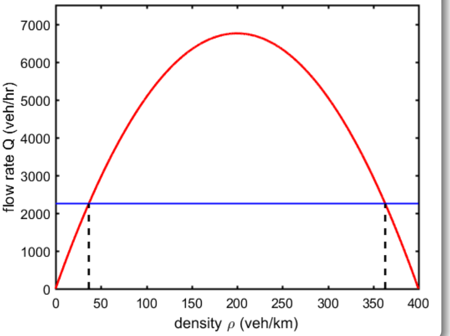
At a fixed position, maximum flux (throughput) gets limited (accident, road feature, etc.).

Two possibilities:

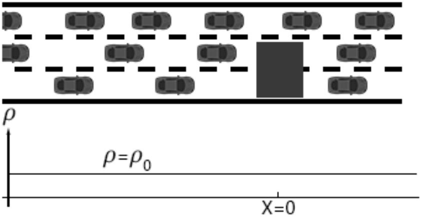
(a) Incoming flow is below bottleneck flow $\Longrightarrow$ no effect.

(b) Incoming flow exceeds bottleneck flow $\Longrightarrow$ two new states arise: one congested, one free flow.

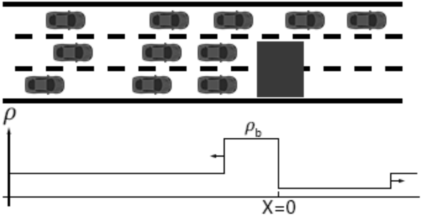
New states in FD



Bottleneck (lane closure) occurs



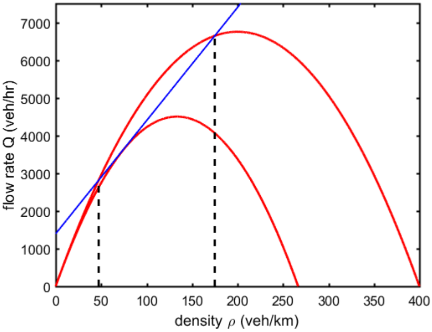
Effect of bottleneck after some time



Moving Bottleneck

- A slow-moving (speed s) vehicle occupies certain lanes.
- Reduced FD corresponding to remaining lanes.
- Now relative flow $Q(\rho) - s\rho$ matters.
- Maximum relative flow (blue line: tangent of slope s).

New states in FD



Two possibilities

(a) Incoming rel. flow below max. rel. flow $\Longrightarrow$ no effect (all vehicles pass).

(b) Incoming rel. flow exceeds max. ref. flow $\Longrightarrow$ two new states arise: reduced density ahead of AV; higher density behind AV.

With moving bottleneck, it is possible that both new states are free flow.

Remark: Neglect short zone of passing and lane changing.

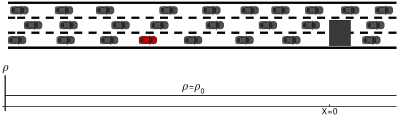
Traffic Flow Control via Moving Bottleneck

- Situation: a few autonomous vehicles are on road.
- Default: all AVs drive like humans.
- Activate control: pick one AV and let it start driving in right lane, slower than the rest.
- If not all vehicles can pass the AV, this control modifies the traffic state on the road.
- Are there situations in which this control can be beneficial?

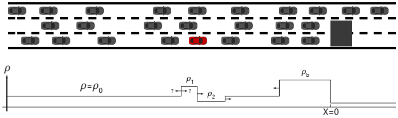
Here is one Important Situation

A fixed bottleneck (blocked lane(s)) occurs.
As a reaction, a moving bottleneck AV gets activated further upstream.

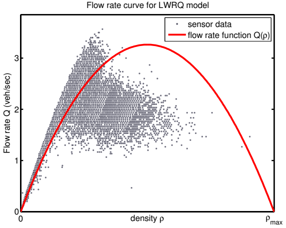
Time of activation of bottlenecks



Effect of bottlenecks after some time



Real Traffic Data



Traffic Flow Model

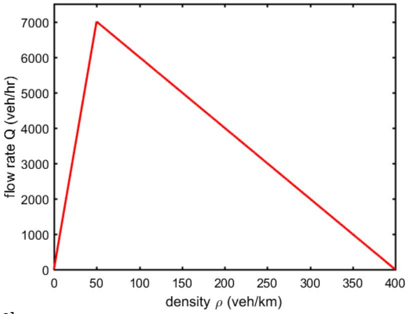
Do not use Greenshields flux. · · · · · · · · · · · · · ⟶

Instead, use LWR model with Newell-Daganzo flux.

Data-Fitted Newell-Deganzo FD

Data representative of highways in Germany (3 lanes):

- jam density: $\rho_\text{m} = 400$ veh/km
- critical density: $\rho_\text{c} = 50$ veh/km
- free flow speed: $u_\text{m} = 140$ km/hr
- capacity: $Q_\text{m} = 7000$ veh/hr

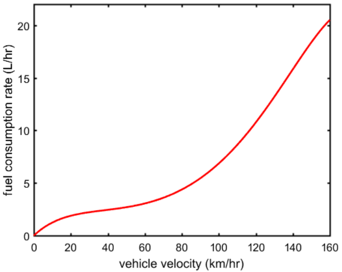


[Ning, W., *A new approach for modeling of fundamental diagrams*, 2002]

Fuel Consumption Rate vs. Velocity

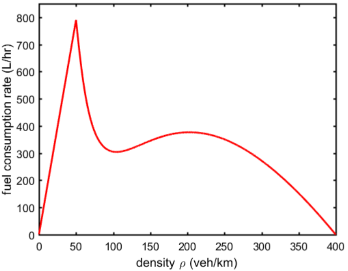
Average of fuel consumption curves $K(v)$ for four representative vehicles (Ford Explorer, Ford Focus, Honda Civic, and Honda Accord).

[Berry, I., *The effects of driving style and vehicle performance on the real-world fuel consumption of U.S. light-duty vehicles*, PhD thesis, MIT, 2010]



Fuel Consumption Rate vs. Density

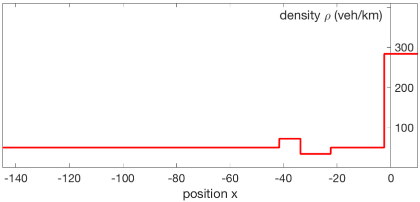
- Combine fuel consumption model with LWR traffic model to obtain fuel consumption rate per vehicle vs. density function $f(\rho) = K(U(\rho))$.
- Shown is density-dependence of fuel consumption rate of all vehicles per unit length: $F(\rho) = \rho f(\rho)$



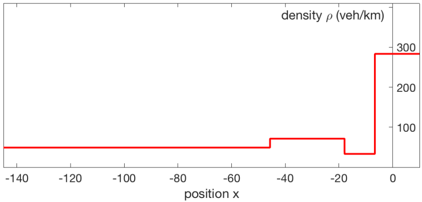
Problem Setup and Control Strategy

- Consider a highway with 3 lanes, with jamming density ρ_m.
- Uniform initial density ρ_0.
- At $t = t_0$, a FB arises somewhere, blocking 2 lanes.
- At $t = t_1$, activate a MB at distance d upstream of the shock induced by the FB, by having an AV drive with velocity s.
- The waves produced by the FB and the MB interact several times.
- Once the AV hits congested state, turn off control.
- Eventually, the effect of the MB vanishes. At that time, every vehicle has traveled precisely as far as it would have without the control. However, with a modified velocity profile over time.
- Therefore, there is no gain or loss in throughput.
- But, the overall total FC changes!
  Can it ever be lower than without control?

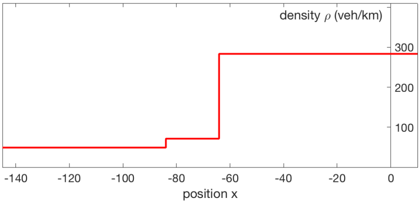
Just After Activation of MB



Just After First Wave Interaction

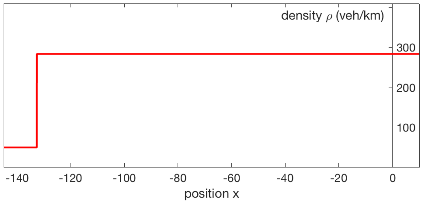


Just After Second Wave Interaction



MB control has just been deactivated.

Just After Third Wave Interaction



Effect of moving bottleneck has vanished.

UNIVERSITY

Calculation of Fuel Consumption Balance

- Two scenarios to react to the FB:
  - *Scenario A:* The MB is not activated (uncontrolled case).
  - *Scenario B:* The MB is activated (controlled case).
- Domain of influence of MB: $\Omega := \{(x,t) \mid \rho_A(x,t) \neq \rho_B(x,t)\}$.
- Total FC in Ω is $G_X^\Omega = \iint\limits_\Omega F(\rho_X(x,t))\,\mathrm{d}x\,\mathrm{d}t$, where $X \in \{A, B\}$.
- Total fuel saved due to MB control: $W = G_A^\Omega - G_B^\Omega$.
- T = total duration of influence of MB.
- Fuel consumption savings rate: $Y = \frac{W}{T}$.

Example (Long Highway)

- $\rho_0 = 45$ veh/km
- $d = 40$ km
- $s = 98$ km/hr < 140 km/hr

Yields fuel savings of $Y = 1087$ liters/hr.
About 1600 Euro/hr (in Germany).

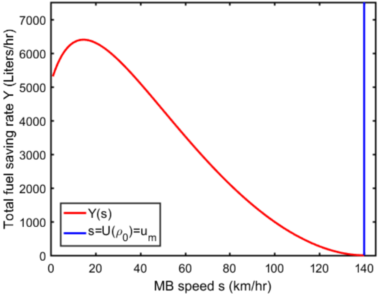
(1) The idea of control via a single MB works!
(2) How good are the savings? $\longrightarrow$ end of talk

Effect of Distance d

- d merely re-scales the density profile with respect to space and time.
- Therefore, Y scales linearly with d: $Y(\lambda d) = \lambda Y(d), \quad \lambda \in \mathbb{R}_+$
- Strategy: maximize d as long as the effects of the MB will have vanished by the time the FB clears.

Optimal Moving Bottleneck Speed

- $\rho_0 = 45$ veh/km. Set $d = 40$ km.
- Plot Y as function of MB speed s.
- Obtain optimal speed s^*.
- In reality, safety constraints restrict s to regime where $Y(s)$ is decreasing.
- Strategy: Choose s as slow as deemed safe.



UNIVERSITY

Conclusions and Discussion

- One AV, serving as moving bottleneck, can be used for traffic flow control.
- Realistic situation yields about 1600 Eur/hr saved. Not bad, given that the control comes at nearly zero cost (need only compensation of AV's "driver").
- Why do we look at situation with fixed bottleneck? So that the controlled case returns to the uncontrolled state eventually (no vehicles, except for AV, held back in the end).
- Reason for fuel savings: rather than driving very fast (air drag!) and then very slowly, vehicles are made to drive at medium speeds for a while.
- The true cost of highly congested flow is completely underestimated in this analysis. LWR neglects unsteady driving; accumulated pollution (many vehicles close together); stress and exhaustion of drivers; etc. In reality, the benefits of the MB control are substantially more significant.
- If capacity drop at fixed bottleneck is considered, then the MB control can actually increase the throughput of the highway (hold back vehicles to clear out congestion upstream of fixed bottleneck).